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Variations and relations of meteorological parameters between upwind and downwind small-scale wind turbine rotor area

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Abstract: Renewable energy sources are becoming increasingly important due to climate change and the energy crisis. Wind energy projects and applications in particular have been growing recently. Meteorological parameters such as wind speed, ambient temperature, relative humidity, and air pressure directly affect wind turbine electricity generation. Understanding the relationships among these parameters is necessary to determine wind energy potential and to predict electricity generation.

The current work is based on data obtained from a 1.5 kW wind turbine constructed in İstanbul Technical University's meteorological park in Turkey. A one minute time interval was used in the data analysis. In this study, upwind/downwind meteorological variables of the wind turbine rotor area were investigated and analyzed in detail. It was observed that the turbine used in this study performs better under low wind speed conditions than under high wind speed conditions.

The difference in relative humidity between the upwind and downwind rotor area reached 4%. It is also important to note that, depending on wind speed, temperature differences between the upwind and downwind rotor area reached 5%. Equations for upwind/downwind variables were obtained for each meteorological parameter.

Key words: Downwind, upwind meteorological parameters, rotor, wind energy, wind turbine

1. Introduction

The importance of renewable energy sources, and especially of wind energy, has grown over the past decades because of their environmental and long-term economic benefits. Wind farms are now found all over the world in an effort to meet growing energy demands through clean energy means.

Several countries provide incentives to clean energy investors. For instance, in Turkey the renewable energy law was revised due to the growing share of clean energy since 2010. Many energy companies have applied to participate following the revision.

However, wind turbine electricity generation has some problems such as discontinuity and low efficiency. Renewable energy sources such as wind, solar, and hydraulic energy are related to meteorological parameters. Feasibility studies to determine a location with high wind potential in order to obtain maximum efficiency have to be carried out prior to the installation of wind turbines. Serious problems are bound to occur if the meteorological characteristics of these renewable energy sources are not well known and understood.

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In the literature there are several studies on wind energy potential and electricity generation [1–15]. In these papers different approaches based on meteorological parameters such as wind speed, temperature, relative humidity, and air pressure have been analyzed. Some of them include only the wind speed parameter in order to determine the potential of wind energy using the Weibull distribution and other methods such as cumulative semivariograms [1–13]. Other studies relate not only the wind speed parameter, but also the ambient temperature, relative humidity, and atmospheric pressure [14,15]. In these works the parameters only refer to input, i.e. upwind rotor area values. However, it is important to know the upwind-downwind rotor area values relation in order to determine system losses and design turbine systems such as turbine blades and micro sitting. The studies mentioned above [1–13] generally relate to the wind potential of various countries such as Turkey, Tunisia, and Greece.

Wind speed variation and changeability are based on time and location. Understanding these characteristics is one of the subjects of spatio-temporal wind modeling. Dynamic and statistical modeling approaches are special considerations in wind power research as they determine the atmospheric boundary layer. Petersen [16] considered wind power meteorology and sought the relationship between atmospheric events and wind power. During the preparation of Denmark's and European Wind Atlases detailed research was carried out on wind energy as an atmospheric energy source [17].

Other atmospheric variables such as pressure, temperature, and moisture play important roles in the dynamic occurrence of wind. Generally, in wind engineering some of these variables such as moisture is negligible and air is assumed to be dry [18–20].

2. System and data

A wind power generation and measurement system was constructed in the meteorological park of İstanbul Technical University in İstanbul, Turkey. This system contains a 1.5 kW wind turbine that shows a cut in wind speed at 2.7 m/s and a survival wind speed at 55 m/s, a 4.8 kW battery system, a charge regulator, an inverter, upwind–downwind anemometers, thermometers, an infrared thermometer, differential barometers, a hygrometer, and a thermal cable to measure the generator temperature (Figure 1). The system was constructed to research the general characteristics of a small-scale wind turbine application under the climatic conditions of İstanbul. The properties of the measurement devices of the meteorological variables are given in the Table. Additionally, one of the favorable aims for constructing this system was to determine the best conditions for wind turbine electricity generation in İstanbul. This area has moderate windy conditions and so a wind turbine that has less cut-in is preferred for this system.

Table. General characteristics of measurement devices of meteorological variables.

Device	Measurement range	Accuracy
Certified cup anemometer	1–96 m/s	0.1 m/s, for the range 5–25 m/s
Infrared thermometer	–40 °C–700 °C	0.03%/°C or 0.05%/°C
Thermometer	–30 °C–80 °C	0.15 °C
Differential barometer	10 mb–200 mb	±0.5% (20 °C)
Hygrometer	0%–100%	±2.5%, from 5% to 95% at 23 °C

The system was installed in the mentioned area in February 2009 and one-minute data were collected. İstanbul is under the influence of a mild Mediterranean climate during the summer. There is rainfall almost throughout the year, but comparatively small values are measured in the summer months and the highest rainfall occurs in the spring months. During the winter İstanbul is faced with the influence of high pressure by the Siberia low-pressure system from inland. Hence, northeastern or southern winds influence the study area with high rainfall amounts and snow every year with cold-wet spells.

3. Application and results

The characteristics of the wind turbine system installed in İstanbul Technical University's meteorological station have been observed under one-minute time intervals since February 2009. It should be noted that wind characteristics and effects are taken into account by using meteorological parameters from upwind to downwind.

Figure 1 represents the ratio between downwind and upwind wind speed values based on a one-minute time scale. It is known that the Betz (1919) limitation gives a theoretical relation between upwind and downwind wind speed. These values show the level of losses caused by the wind turbine blades. Consequently, the blades should be designed to minimize losses. In the current work this ratio is mostly between 0.2 and 0.6 (Figure 2).

Figure 1. Illustration of the wind turbine installed.

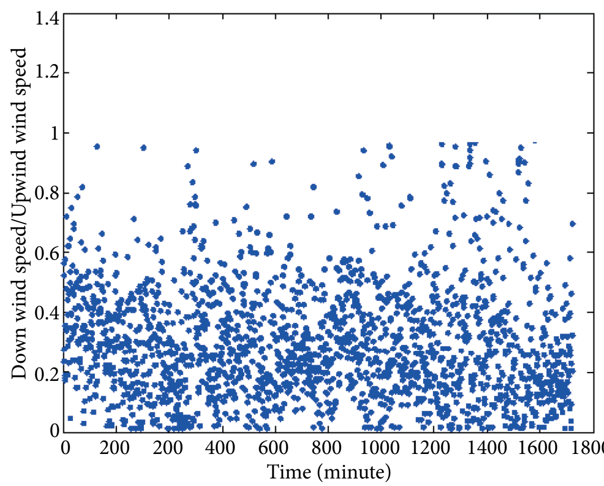

Figure 2. Measured wind speed values.

For high turbine efficiency the desired ratio should approximate the Betz limit. However, some problems related to the design of the turbine blades cause a decrease in the usage of wind speed from upwind to downwind. In the current application sometimes this ratio increased to approximately 1.0, which means that at those times the blades could not generate wind energy (Figure 2). In addition, as seen in Figure 2, there is a high scatter for the considered ratio. To solve this problem, the averages are considered for each time interval. It is clearly determined that there is a nonlinear relation between the mentioned parameters (Figure 3). According to the Betz limit (1919), the maximum usable wind speed ratio is 59%. In other words, the maximum waste wind speed ratio is 41%. In the current work the downwind wind speed/upwind wind speed ratio is considered to determine the aerodynamic efficiency of small-scale wind turbine blades. It was observed that most of the time this ratio was higher than 41%. This means that the blades of this turbine are not optimally designed for aerodynamic efficiency (Figure 3).

Relative humidity is another meteorological parameter considered in this study. Upwind (or input) and downwind (or output) relative humidity values were measured. It is important to note that the relative differences between upwind and downwind relative humidity increased to 4% time to time. This means that the turbine blades do not allow air mass movement from upwind to downwind and cause these relative humidity differences. Our work is the first to describe this situation in the literature (Figure 4).

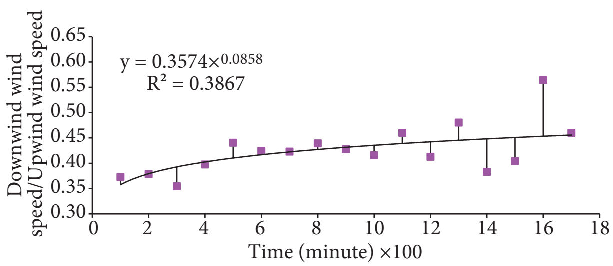

Figure 3. The ratio of downwind speed values to upwind speed values.

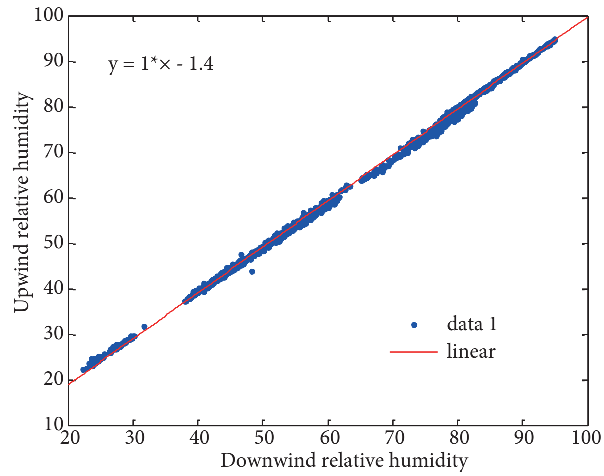

Figure 4. The difference of relative humidity between upwind and downwind.

As known, entropy generation of fluid is related to pressure differences between upwind and downwind of the wind turbine rotor area. In this study the pressure differences were taken into account and it was observed that the relative difference sometimes increased to 0.1% (Figure 5).

Another important meteorological parameter is temperature. Relative differences between upwind and downwind rotor area temperatures increased to 5%. This means that there is an important temperature difference when wind speed changes. Generally, the wind speed and temperature relation is considered as a wind chill effect for human skin. However, it is seen that a new wind chill index should be developed for shelters that block wind systems depending on their porosity (Figure 6).

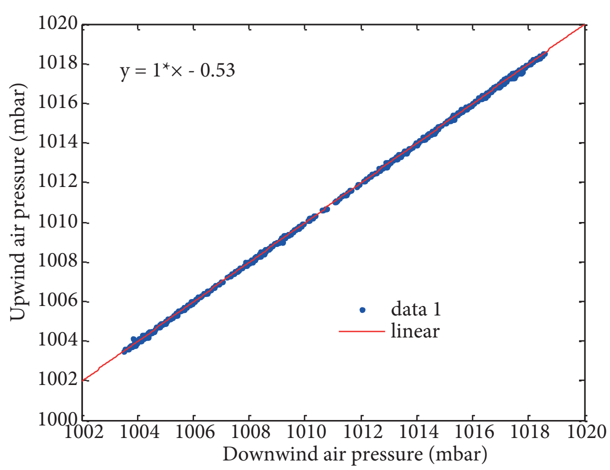

Figure 5. The relative difference of pressure measured.

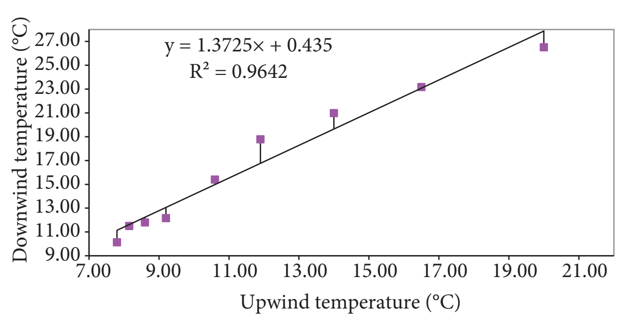

Figure 6. Relation between downwind and upwind temperatures.

Figure 7 represents the internal variation of the wind turbine (generator, temperature with time). It can be seen that there is some periodicities during the day.

Figure 8 represents wind turbine inside generator temperature values related to wind speed values. The temperature of the generator increases with wind speeds. The wind speed values were mostly observed between 3 and 5 m/s. Additionally, wind turbine generator temperatures change at different levels depending on ambient temperature (Figure 8).

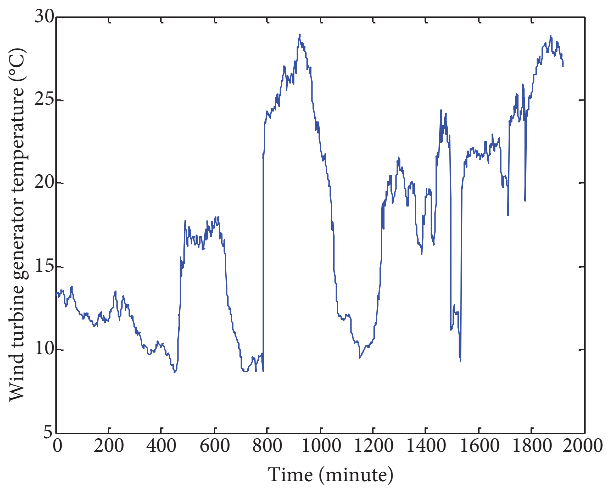

Figure 7. Wind turbine generator temperature.

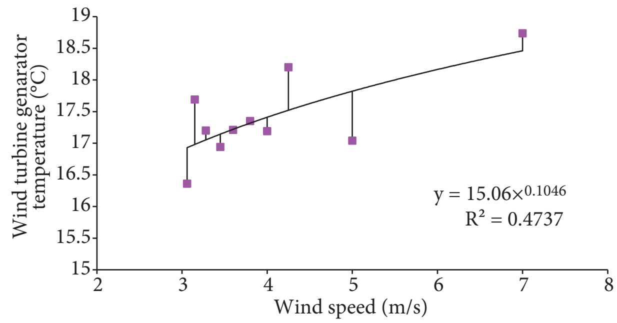

Figure 8. Relation between wind speed and turbine generator temperature.

Figure 9 represents the relation between wind turbine generator temperature and upwind temperature values. A quadratic equation was obtained from this relation. If the ambient temperature value is known, the wind turbine generator temperature can be easily calculated using this equation.

So far we have considered in detail wind turbine general behaviors in terms of the stated meteorological parameters. However, for practical and engineering applications general rules and equations should be evaluated.

The relation between generated electricity and wind speed is very important for wind turbine performance. This relation allows us to use the power curve as a practical tool for wind turbine applications. It was not easy to find a relationship between wind speed and generated electricity due to the highly scattered data. We solved this by averaging both the generated electricity values and the wind speed values. For general rules and equations, wind speed and generated electricity data were grouped and mean values of these groups were obtained. This new data group was then considered to determine general equations for the considered system in this study (Figure 10).

For the variation in Figure 10 a cubic equation was obtained. Consequently, if the wind speed value is given, the electricity generated by the wind turbine can be easily calculated using that equation. In the considered area, unfortunately, wind speed values higher than 8 m/s were not observed.

Some procedures are applied to other variables. Figure 11 represents the relation between upwind and downwind wind speed values. It is seen that there is a high linear relation between these parameters.

Figure 12 shows the relation between generator temperature values and upwind wind speed values. Here, this second degree quadratic equation lets us calculate generator temperature values using upwind wind speed values (in case the generator values are not known).

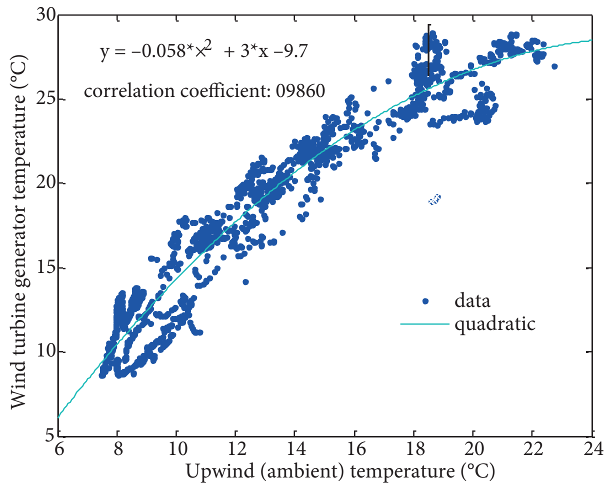

Figure 9. Relation between upwind ambient temperature and generator temperature of the wind turbine.

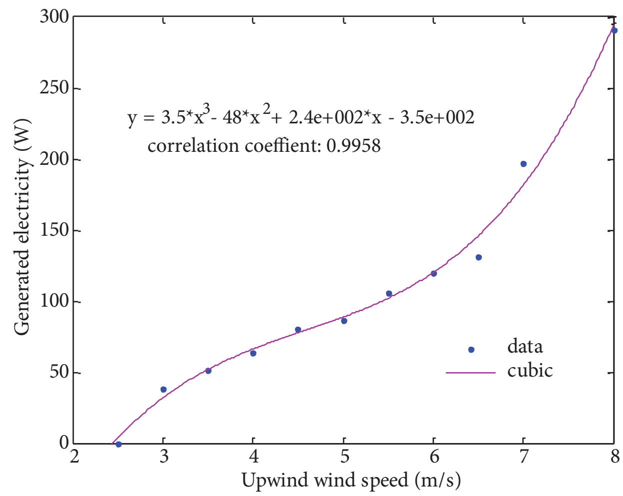

Figure 10. Relation between the average values of electricity generated and the average wind speed values of the wind turbine.

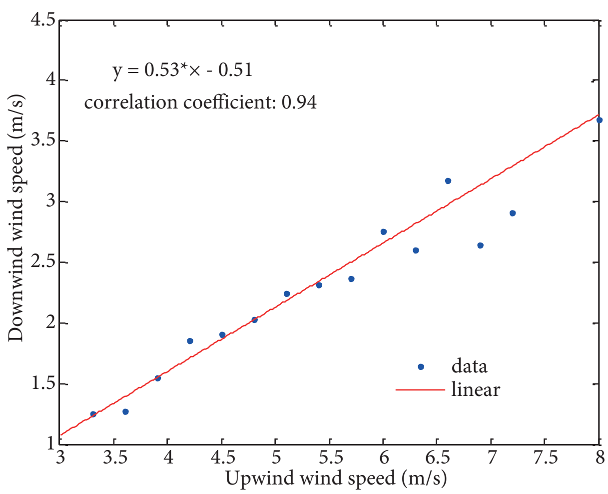

Figure 11. Relation between means of downwind speed and upwind speed values.

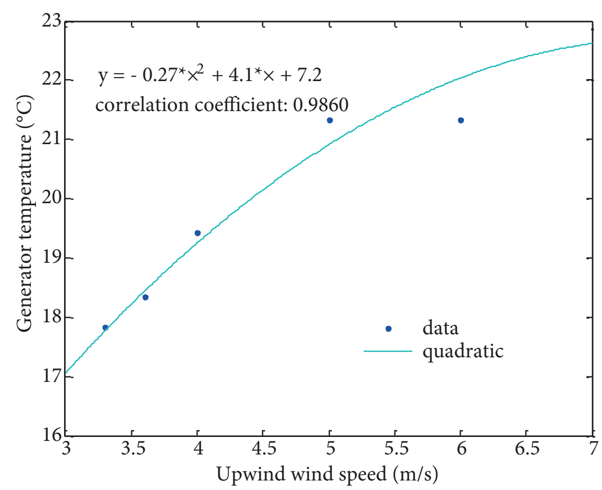

Figure 12. Relation between generator temperature and mean upwind speed values.

In addition, other meteorological parameters such as ambient temperature and upwind side relative humidity are considered. Figure 13 represents how ambient temperature and relative humidity values change with time on a one-minute time horizon. As can be clearly seen, the values of both parameters show inverse variations. In other words, as expected temperature values increase, relative humidity decreases and vice versa.

4. Conclusion

The variations and relations of meteorological and wind turbine parameters were researched in detail. A high relationship between upwind and downwind wind speed values was shown. The considered wind turbine was determined to be aerodynamically ineffective as it could not use effectively upwind wind speed. In addition, there is an important difference between the temperatures of upwind and downwind rotor area sides. It was also observed that there is an inverse relationship between upwind temperature and relative humidity values.

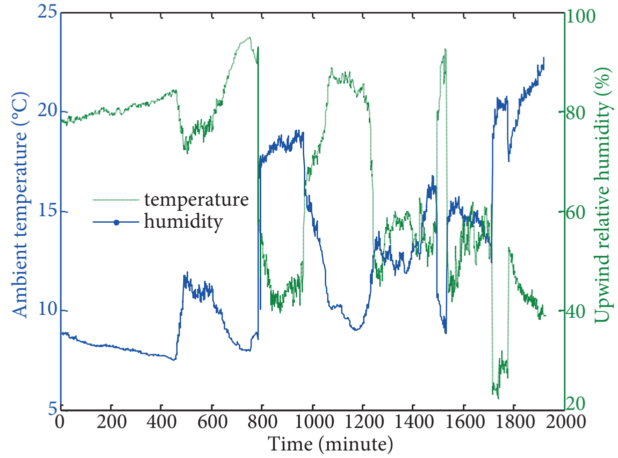

Figure 13. Variation in ambient temperature and upwind relative humidity across time.

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